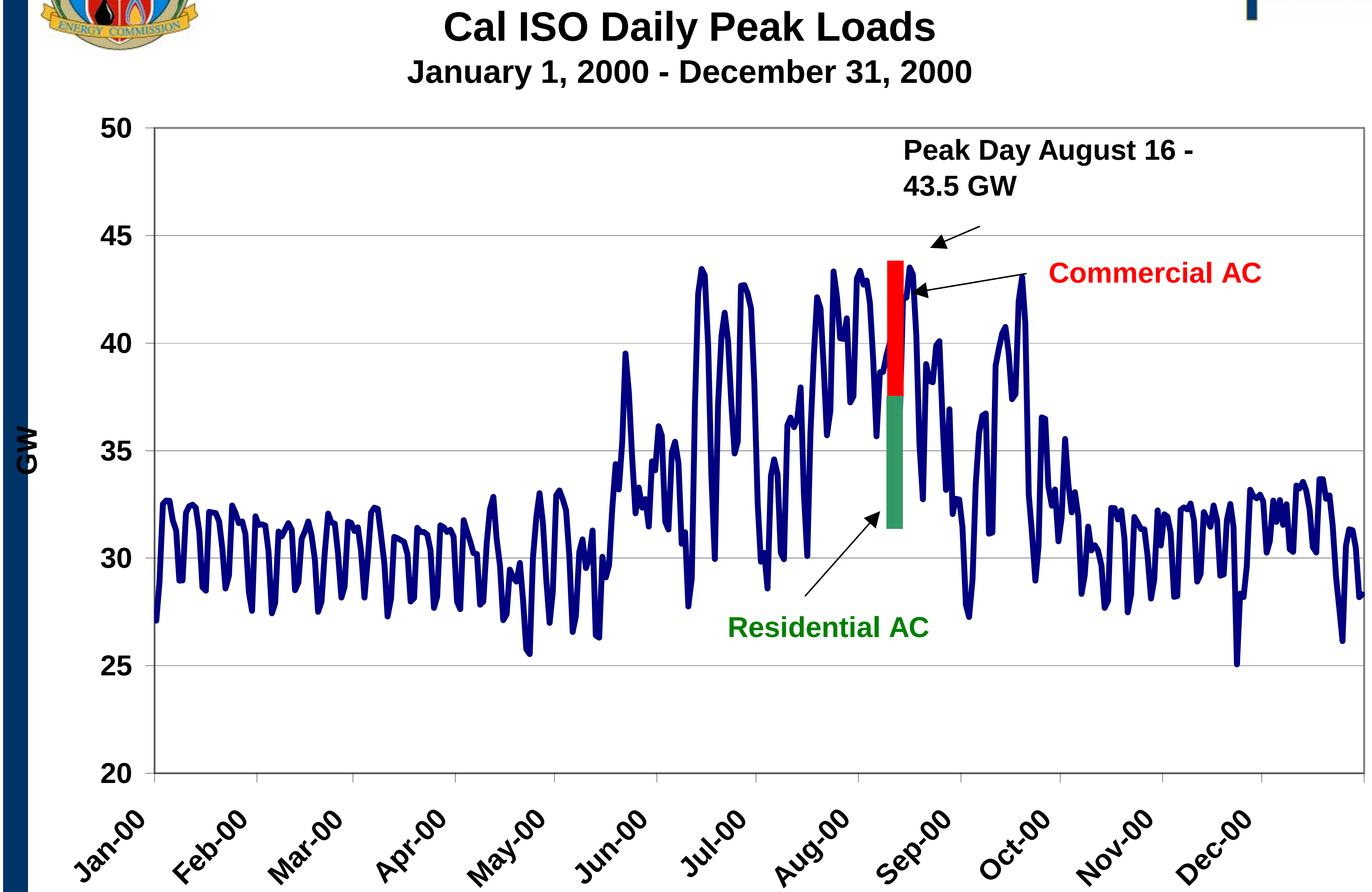
The California Challenge



Options

- Supply-side solutions (building more power plants in our back garden!) to provide for peak demand or system emergencies cost up to 10x more than some demand-side solutions
- In 2000-1, less than 5% “automated” load reduction could have avoided blackouts
- Air conditioning is the ‘low-hanging fruit’
- A real-time control and communications infrastructure is required to support an automated demand response (DR) system

Courtesy: Ron Hofmann

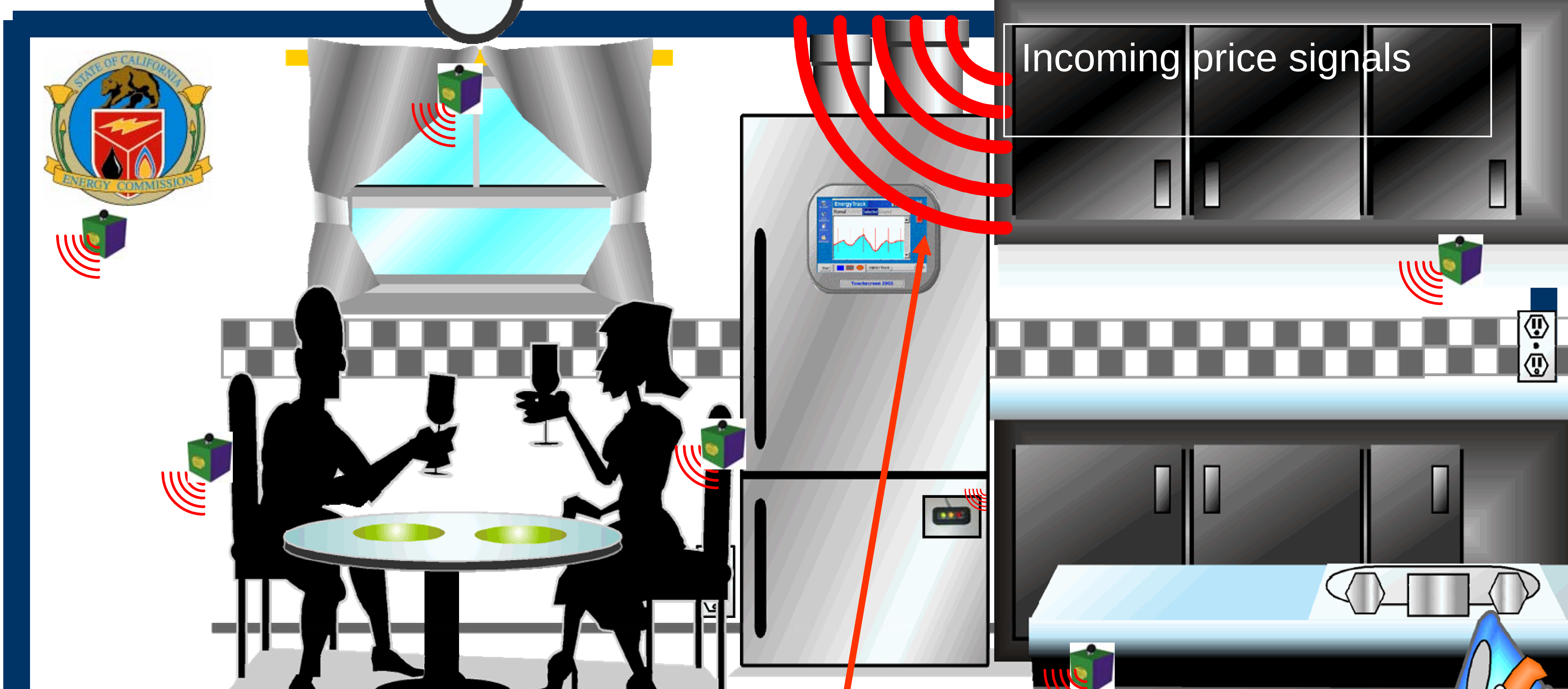
Demand Response

- **Demand response (DR) is the action taken to reduce load when:**
  - Contingencies (emergencies & congestion) occur that threaten supply-demand balance, and/or
  - Market conditions occur that raise supply costs
- **DR typically involves peak-load reductions**
  - DR strategies are different from energy efficiency, i.e., transient vs. permanent

Courtesy: Ron Hofmann

DR ETD – Summary of New Thermostat, TempNode, & New Meter (UC Berkeley Project 6/6/06)

- **New Thermostat, New Temperature Node, & New Meter**
- **Phase One: 3/2003 – 8/2005; Phase Two 9/2005 – 8/2007**
- **Multi-disciplinary Collaboration Team:**
  - David Auslander: ME Dept.
  - Ed Arens & Charlie Huizenga : Center for Built Environment
  - Kris Pister: Berkeley Sensor & Actuator Center, EECS Dept.
  - Jan Rabaey: Berkeley Wireless Research Center, EECS Dept
  - Dick White: Berkeley Sensor & Actuator Center, EECS Dept.
  - Paul Wright: Berkeley Manufacturing Institute, ME Dept.
  - 20 Graduate Student Researchers (13 are funded)
    - Many thanks to all colleagues and students for their contributions



One Vision for Demand Response in CA

1. **<u>New Thermostat</u> with touchpad shows price of electricity in ¢/kWhr + expected monthly bill.**
***Automatic adjustment of HVAC price/comfort.**
***Appliance nodes glow-colors based on price.**
2. **<u>New Meter</u> conveys real-time usage, back to service provider**
3. **<u>Wireless beacons</u> throughout the house allow for fine grained comfort/control**

Appliance lights show price level & appliances powered-down

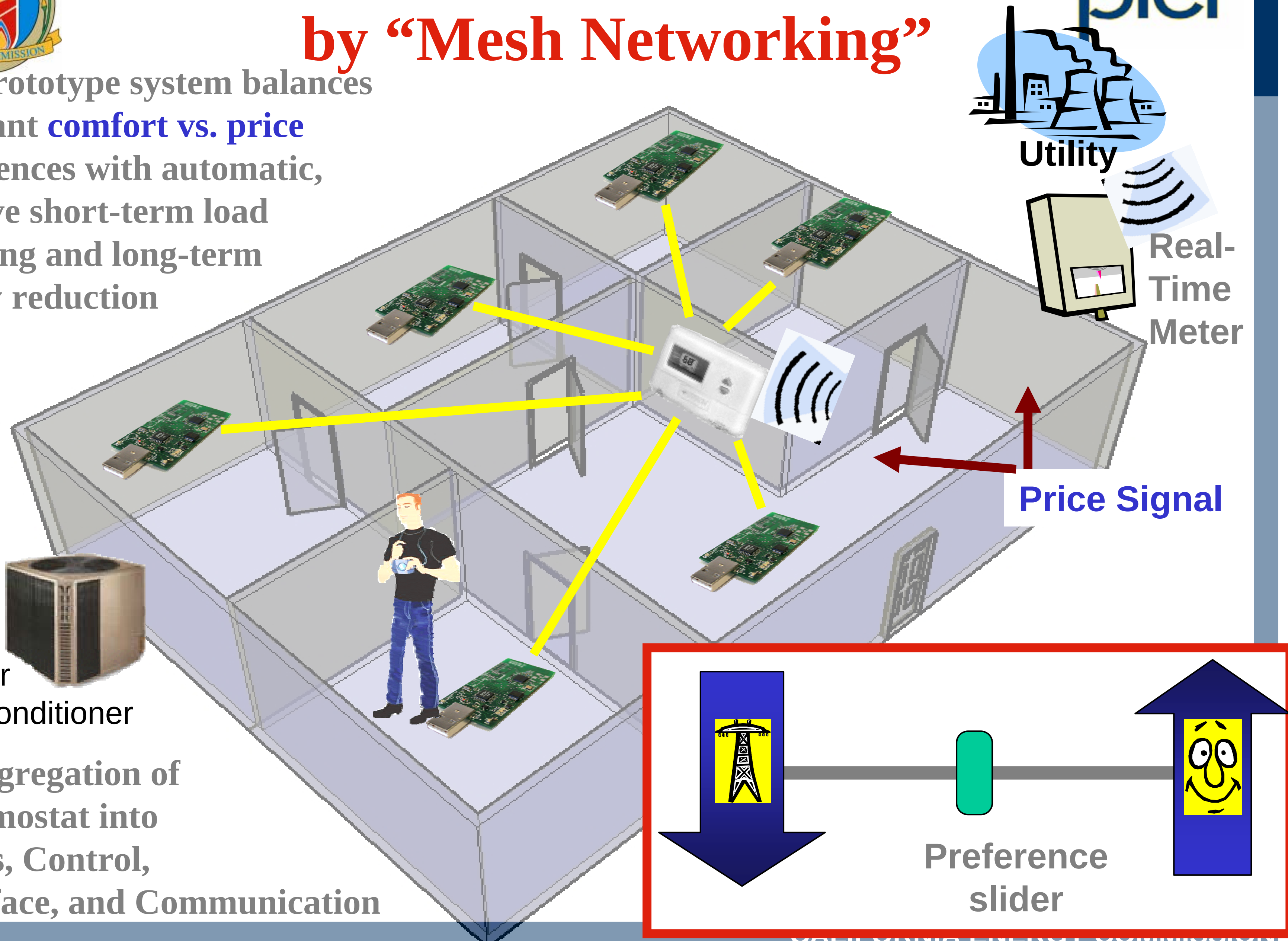
CALIFORNIA EN

DR ETD Project Overview

- **Mid- to long-term R&D (3-8 year objectives)**
  - To help achieve a DR Infrastructure in California
- **Enabling technologies R&D with 10x10x10 goals – not product development**
- **Multi-disciplinary with 4 collaborative sub-teams**
  - 1. Communication 2. Control 3. Sensing 4. Power Supply
  - Leverage DARPA, DoE, NSF, Intel, and other funding
- **"Disruptive"– 10x10x10 improvements, e.g...**
  - 1. Tiny OS (ad hoc self organizing networks)
    Pico radio (low-cost, low-power wireless)
  - 2. Learning algorithms (individualized DR response)
  - 3. Smart Dust (highly integrated control platform)
  - 4. Energy Scavenging (avoid replaceable batteries)

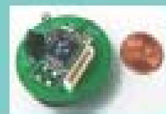
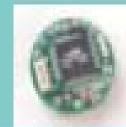
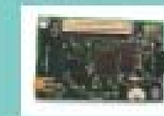
Sub team 1: Radio Communication by “Mesh Networking”

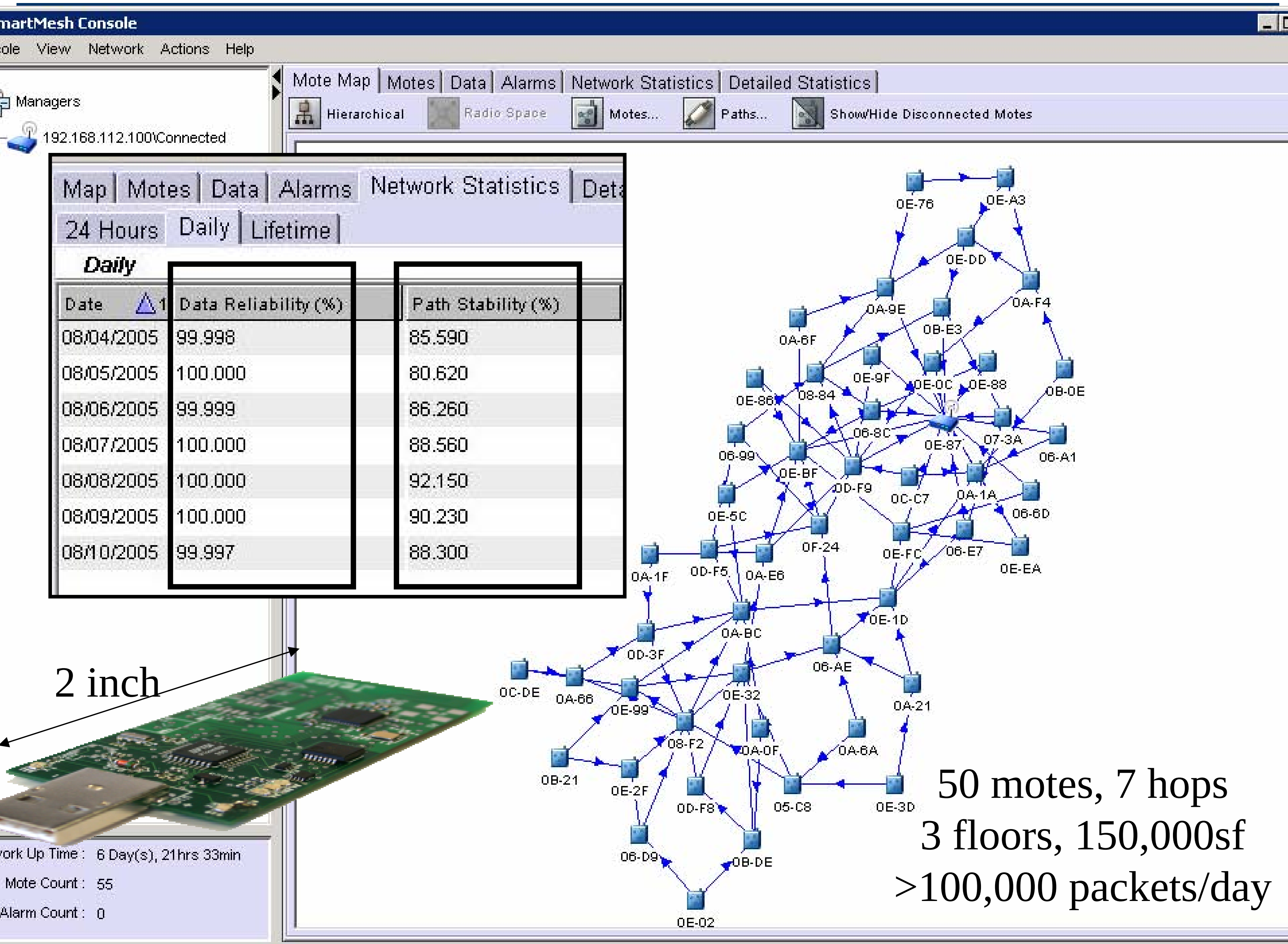
Our prototype system balances occupant **comfort vs. price** preferences with automatic, reactive short-term load shedding and long-term energy reduction



Disaggregation of Thermostat into Nodes, Control, Interface, and Communication

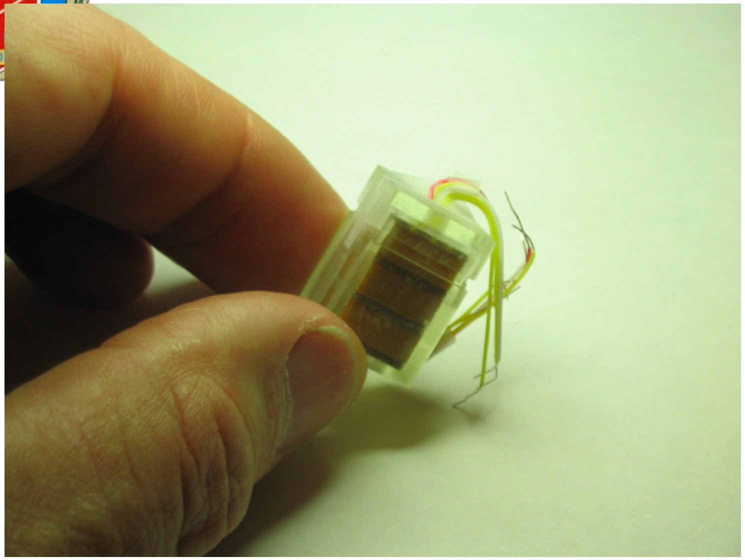
Hardware used with today's Telos 06 device

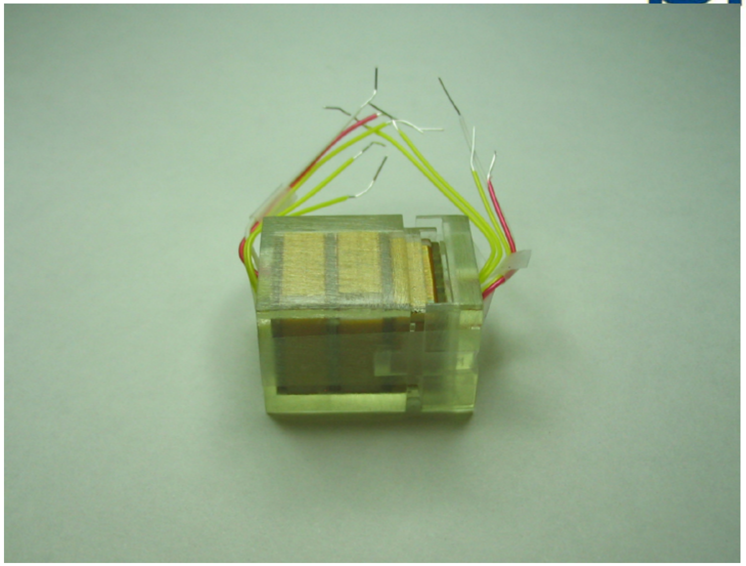
	WeC 1998	*René* 1999	*René 2* 2000	*Dot* 2000	*Mica* 2001	*Mica2Dot* 2002	*Mica 2* 2002	*Telos* 2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega128			TI MSP430
Program memory (KB)	8		16		128			60
RAM (KB)	0.5		1		4			2
Active Power (mW)	15		15		8		33	3
Sleep Power (μW)	45		45		75		75	6
Wakeup Time (μs)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	41
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

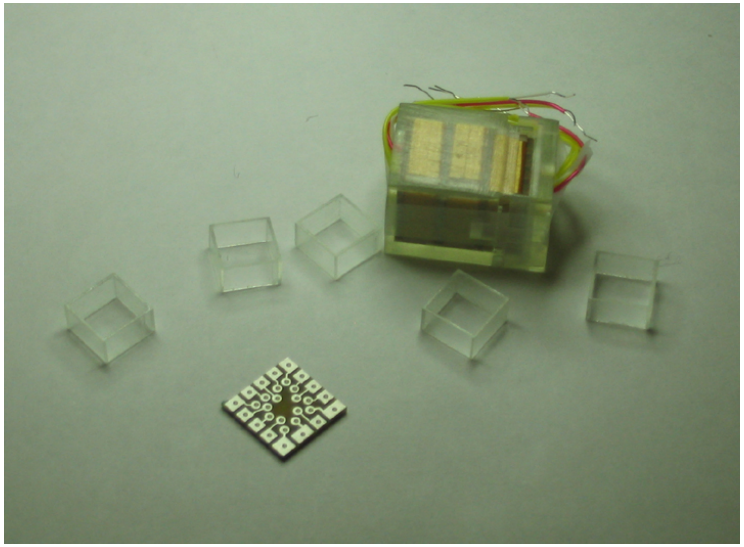


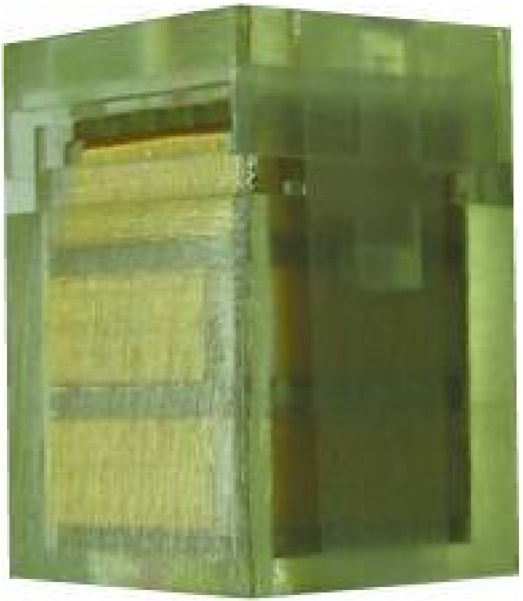
Date	Data Reliability (%)	Path Stability (%)
08/04/2005	99.998	85.590
08/05/2005	100.000	80.620
08/06/2005	99.999	86.260
08/07/2005	100.000	88.560
08/08/2005	100.000	92.150
08/09/2005	100.000	90.230
08/10/2005	99.997	88.300

Towards 10x lower cost: PicoCube Prototype

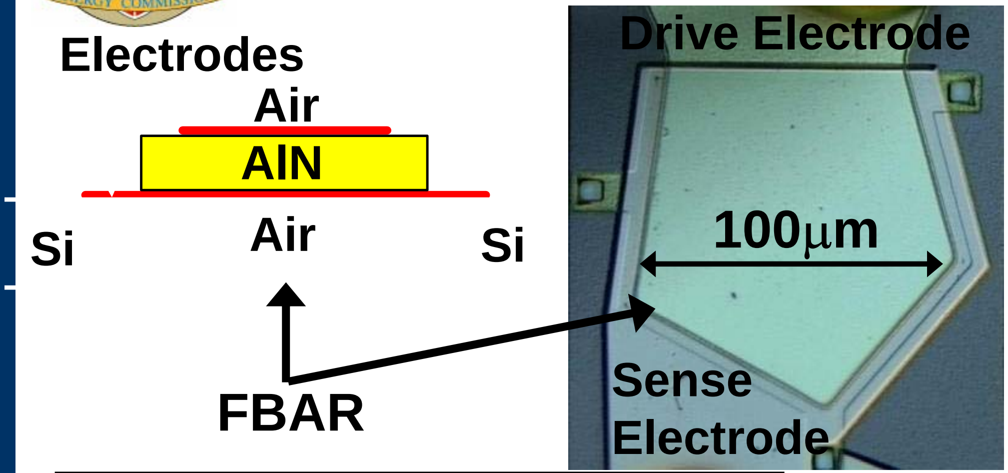






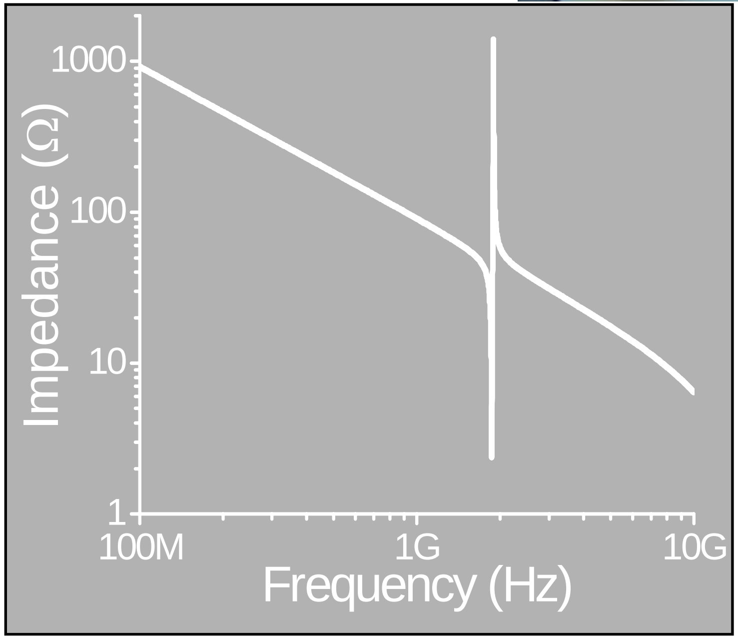


Extensive Use of Innovative MEMS

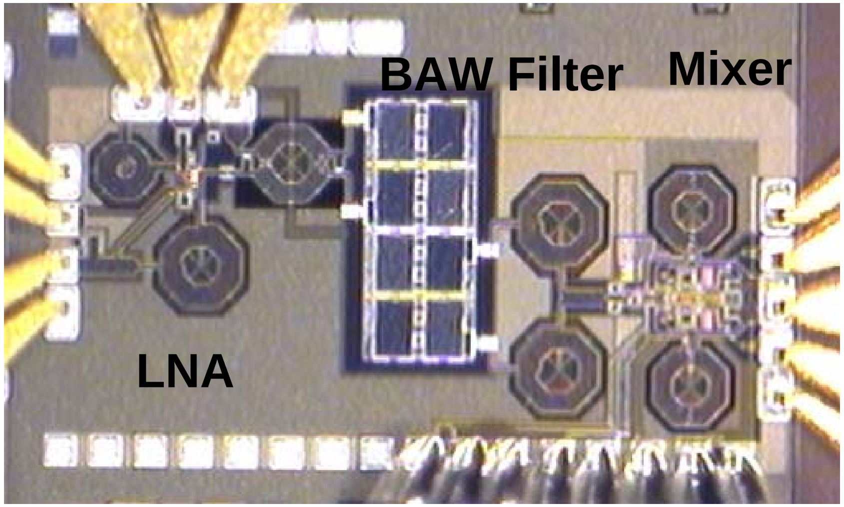


Small form factor

- **MEMS/CMOS co-design**
- **Integration into IC process**



Ruby et. al. (Ultrasonics Symposium 2001)



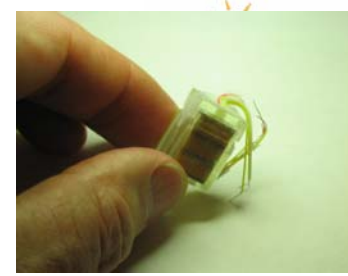
Carpentier et. al. (ISSCC 2005)

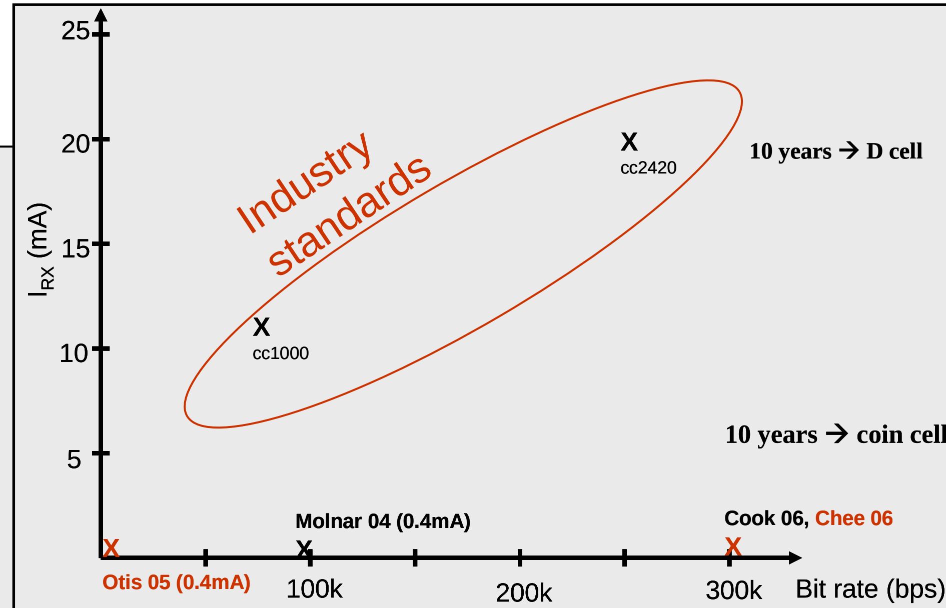
Two radio projects both aiming at 10x10?

- **"FBAR route" explores new MEMS technology for design (uses OOK)**
- **Pros:**
  - Simple design with MEMS simplifies oscillator
  - Fixed at one frequency
  - Will get to lower power levels
- **"CMOS optimized" using passive gain thru LC network (uses FSK)**
- **Pros:**
  - Standard CMOS
  - Tuneable (1.9-2.4 GHz)
  - Robust with noise linearity similar to commercial devices
  - More flexible design

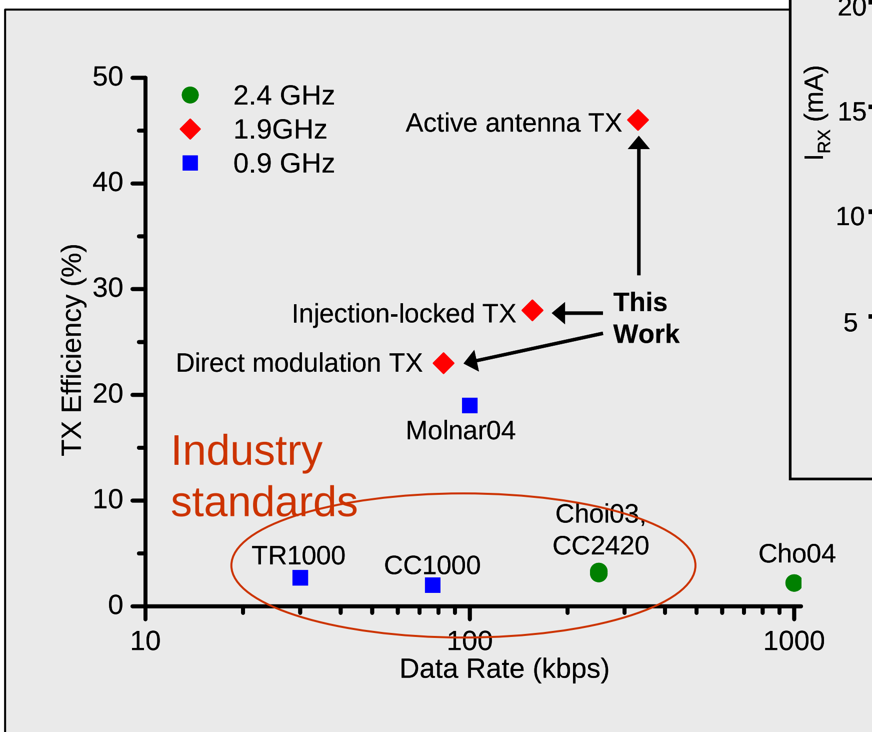
Courtesy: J. Rabaey, K. Pister

Radio Performance summary and the exciting year(s) ahead





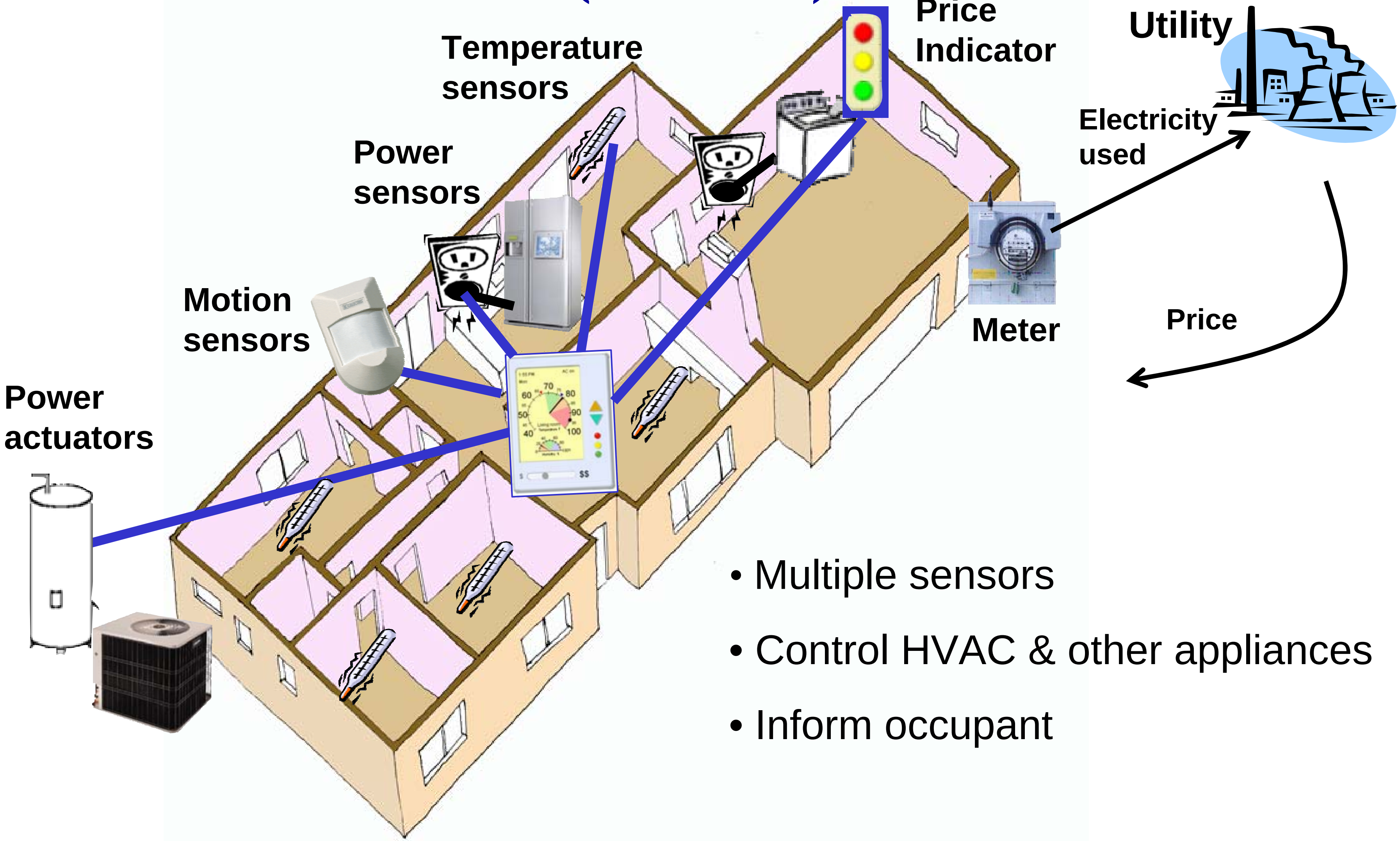
Ultra Low Power Receivers



0 dbM Transmitters

Courtesy: J. Rabaey, K. Pister

Demand Response Electrical Appliance Manager (DREAM)



- Multiple sensors
- Control HVAC & other appliances
- Inform occupant

DREAM Control Code

Control of simulated, model, or real houses

Controller

Java

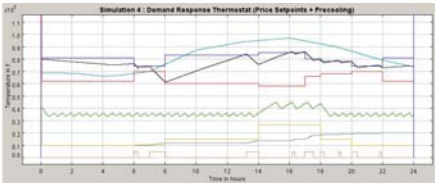
Sensor/ Actuator Module

Java

Interface

XML

Simulation



RF

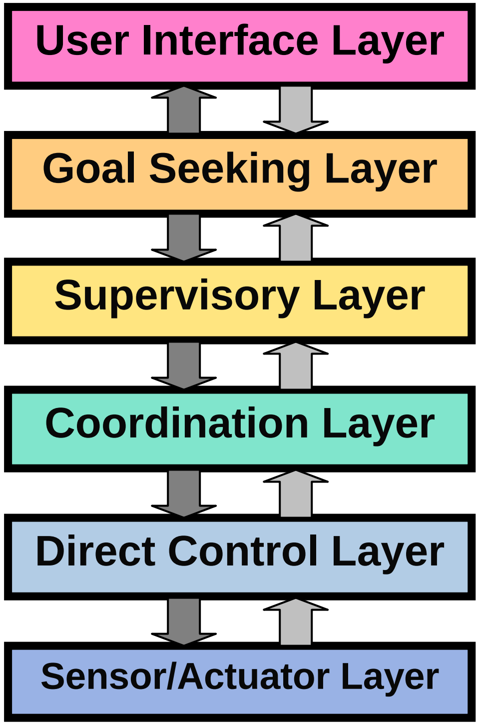
Physical Model

RF

Real House

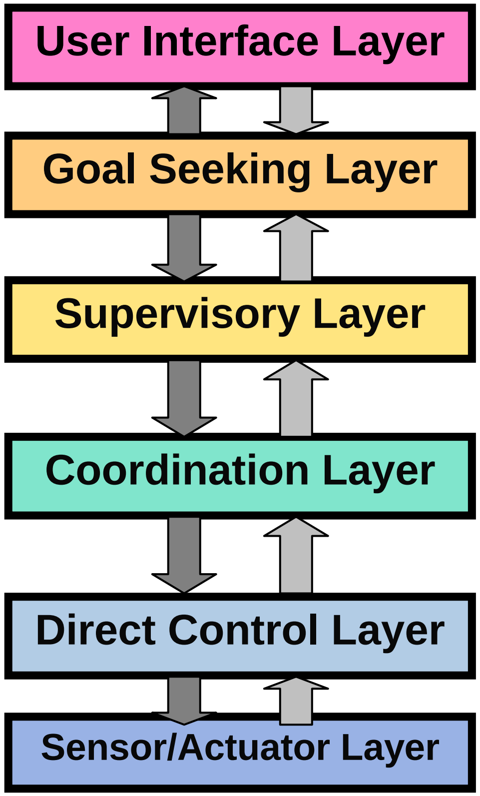
System Control

- Layered control
- Used to build control software for experiments to-date
- Next challenge:
  - Autonomous behavior



Example of Query

Assessing potential for precooling



Q: What is user's temperature preference?
A : 75F

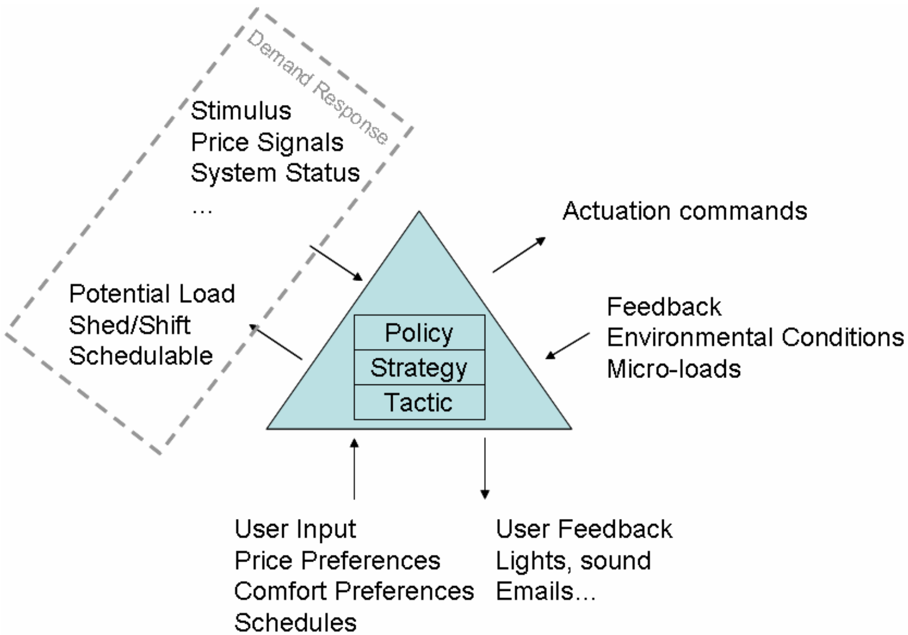
Q: How much power is required to sustain desired temperature in normal mode versus pre-cooling mode?
A : 2500W (pre-cooling mode), 800W (normal mode)

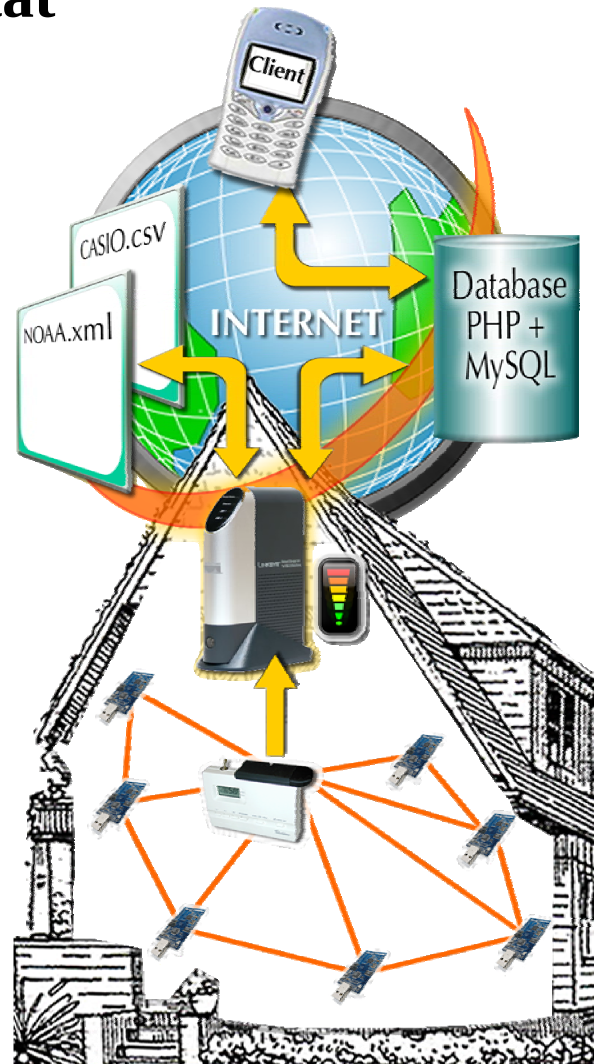
Q: Which device uses least power to sustain desired temperature in normal mode versus pre-cooling mode?
A : Whole house fan

Q: How much power is required for each device to keep temperature at desired value?
A : 500W(whole house fan) , 2500W(AC)

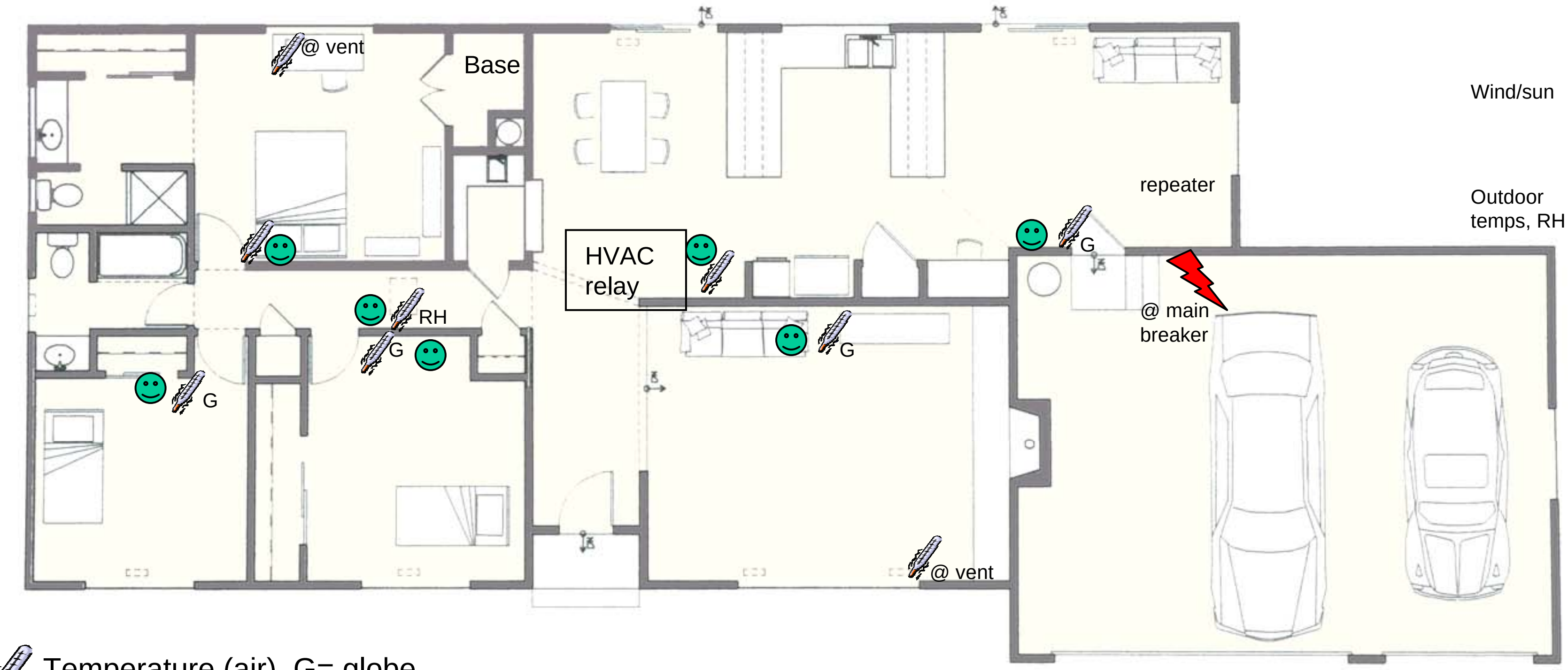
The Residential Energy Manager

- Uses modified standard thermostat





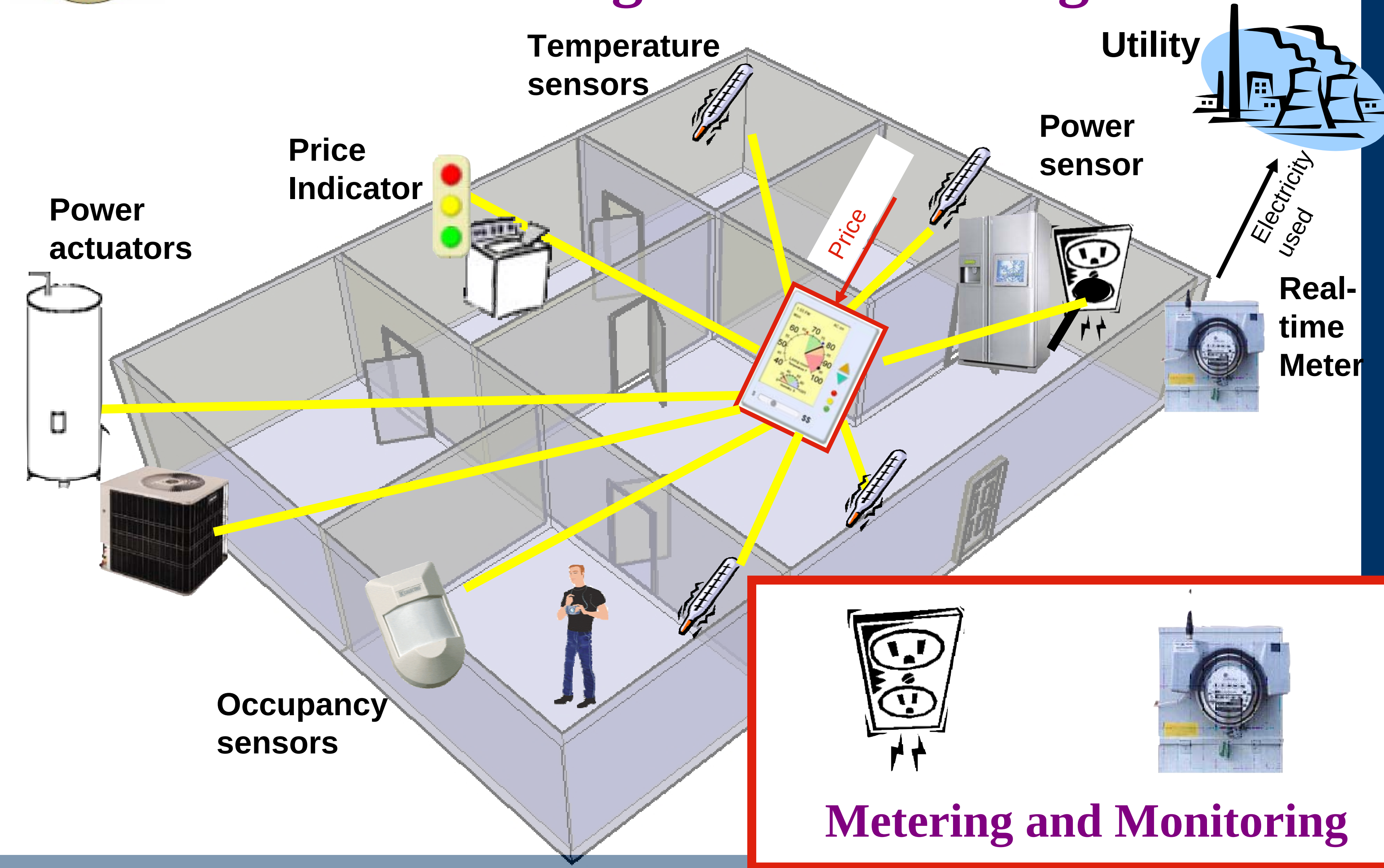
House Test 2005: System Integration



- Temperature (air), G= globe
- Temperature (air) + RH
- Occupancy
- Power sensing (breaker panel)

Weather station on roof (not shown)
Anemometer (wind direction and speed)
Pyranometer (total horizontal radiation and diffuse radiation)
Outside Temperature (exposed to night sky, not exposed)
Outside RH

Sub-team #3: Sensors for Metering and Monitoring

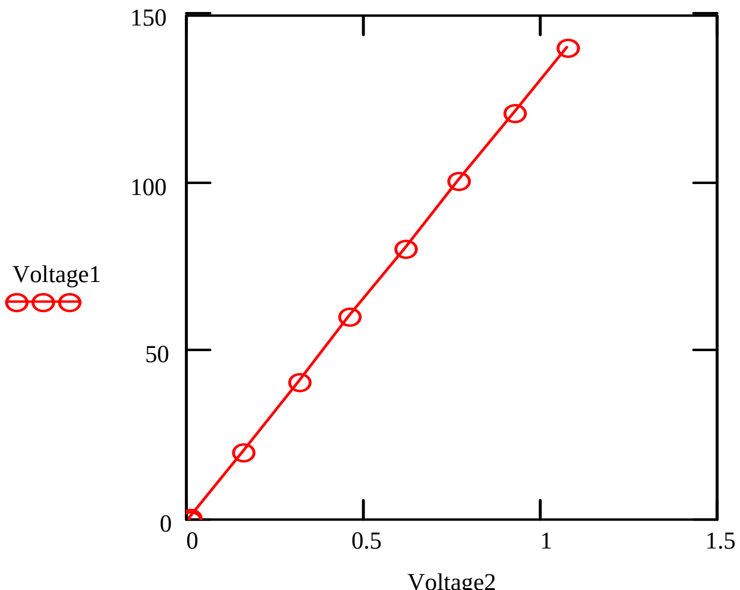


Challenge: Make sensors for AC voltage and AC current that are passive and operate in close proximity to insulated AC wiring?

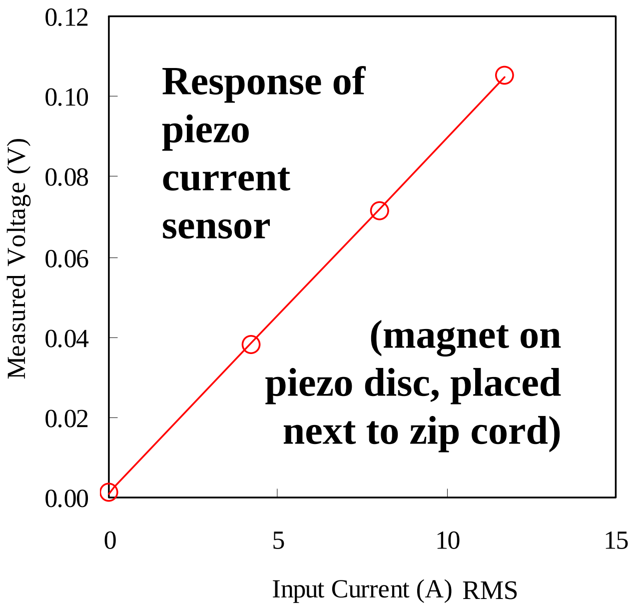
Passive so they don't require DC power source (replaceable batteries)

Proximity so we don't have make conductive contact to wiring

AC Voltage sensor: Electrostatically couple electrodes near insulated wires and detect using analog/digital converter on wireless mote for transmission:

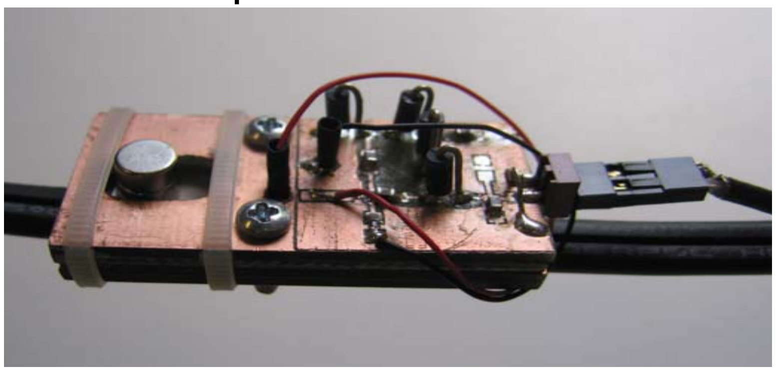


AC current sensor: Locate piezoelectrically-coated cantilever with attached magnetic material near current-carrying insulated wires. Output voltage is proportional to peak electric current.

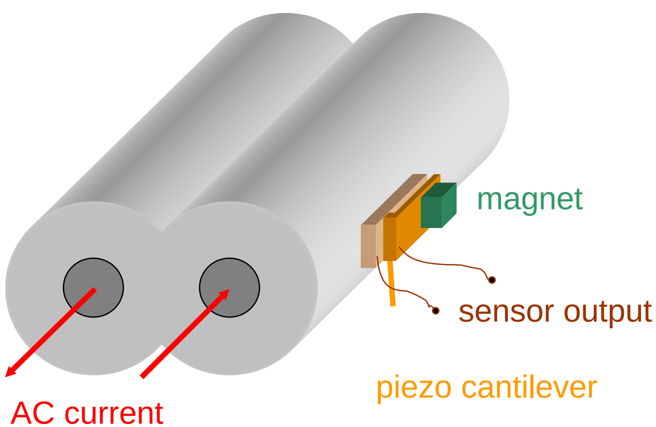


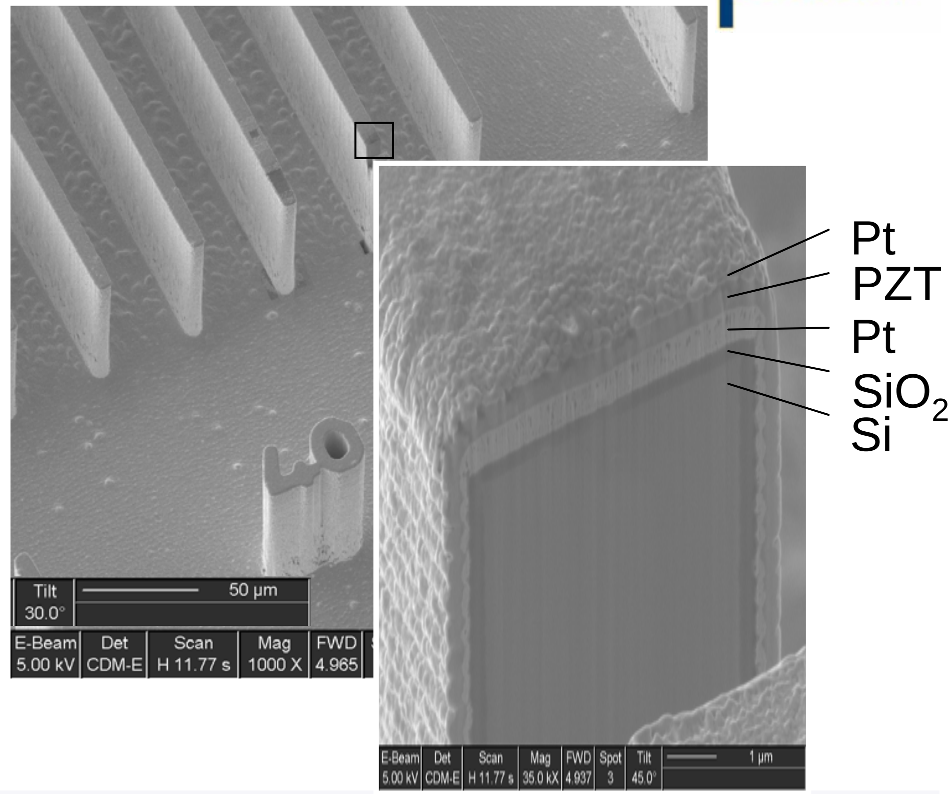
Proximity Current Sensor

Meso-scale current sensors on zipcord with permanent magnet on cantilever coated with piezoelectric



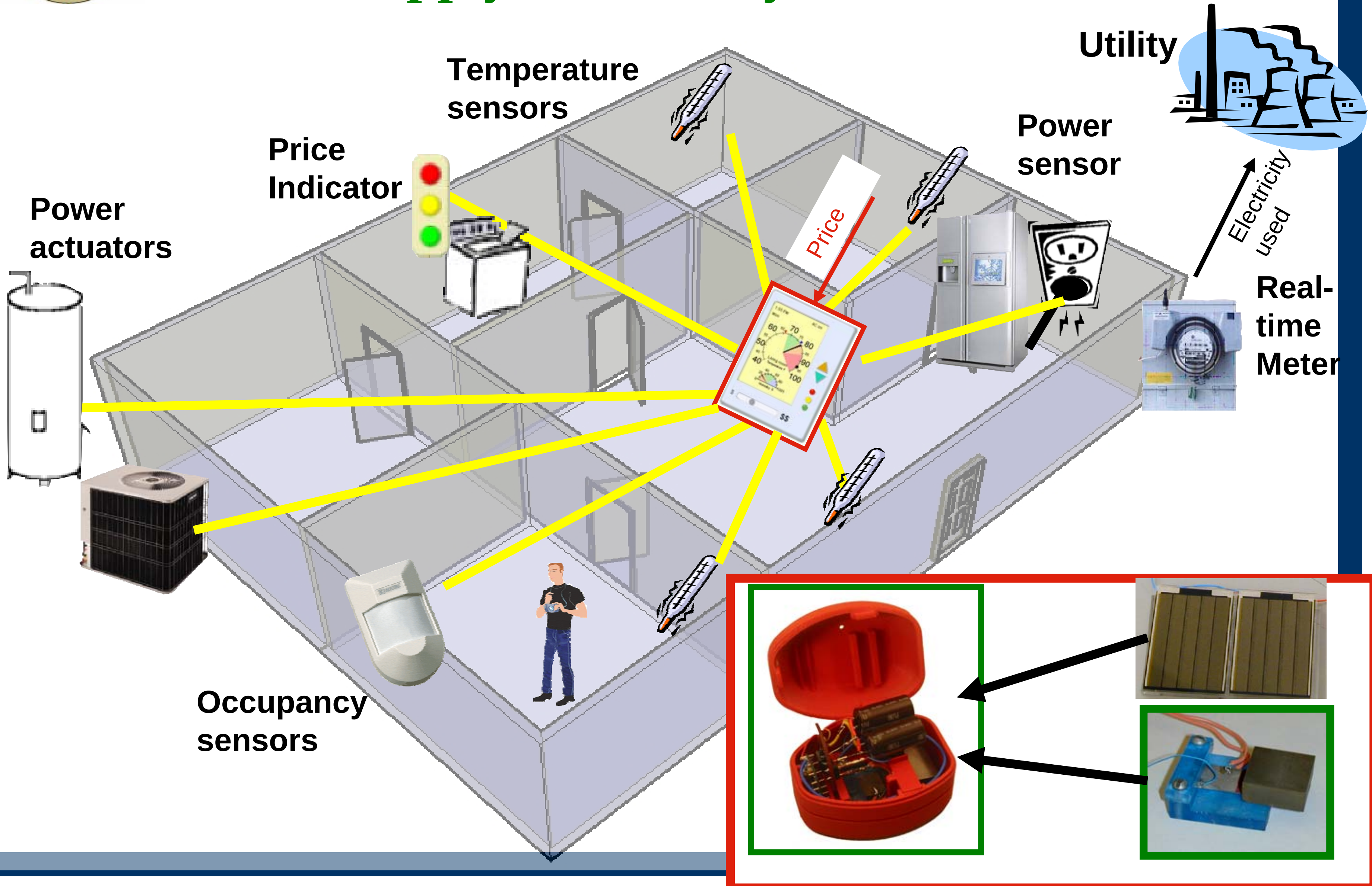
Proposed MEMS-based AC current sensor



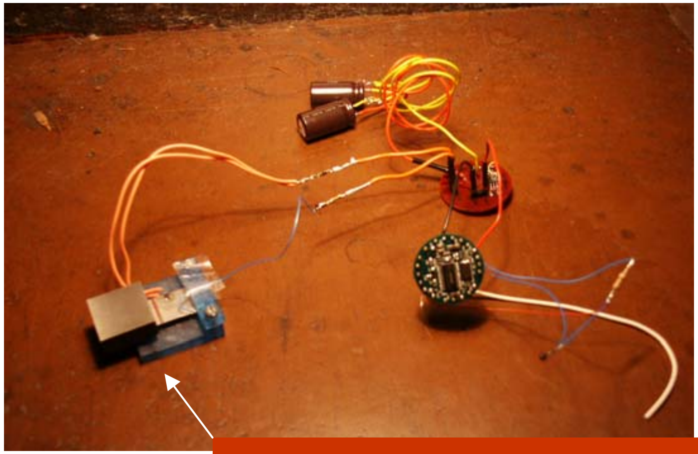


PZT film on sidewalls creates piezoelectric bimorph structure

Sub-team #4: The power supply for the tiny devices



Environmental vibrations

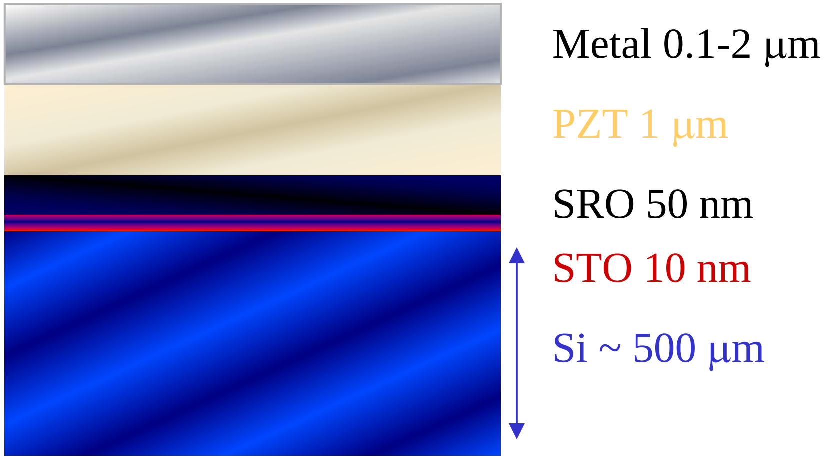


- Stair-Case Vibrations from Running Up and Down Stairs
- Piezoelectric: PZT
- Tungsten Alloy Mass: 52 g
- Beam Dimensions:
- 1.25” x 0.5” x 0.02”
- Resonant Frequency: 26.8 Hz
- Power Output: 450 µW

Piezoelectric “diving board” with tungsten mass

Cost reduction @ MEMS scale

Piezoelectric and Elastic Layers



1. $SrTiO_3$ (STO) coated (10 nm) single crystal Silicon **[Motorola, Inc.]**

2. Deposition of $SrRuO_3$ (SRO) bottom electrode, and PZT with pulsed laser deposition.

3. Deposition of metallic elastic layer via e-beam evaporation/thermal evaporation

Elastic Layer Deposition Methods

*__Pt-__ electron beam evaporation, Ti adhesion layer

*__Ni-__ thermal evaporation

*__Au-__ electron beam/thermal evaporation, Cr adhesion layer

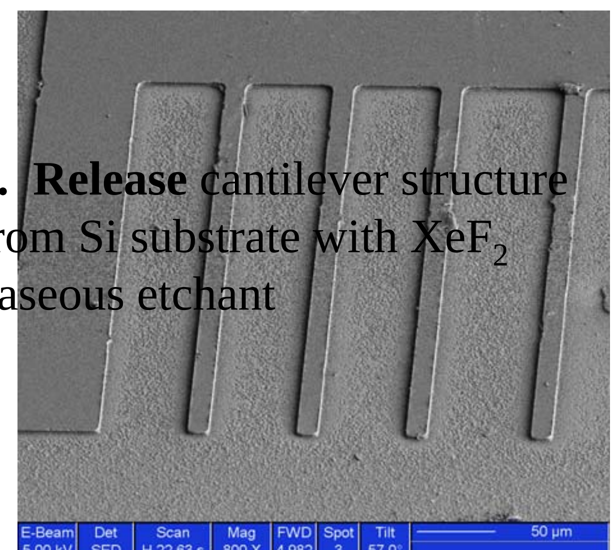
MEMS scale

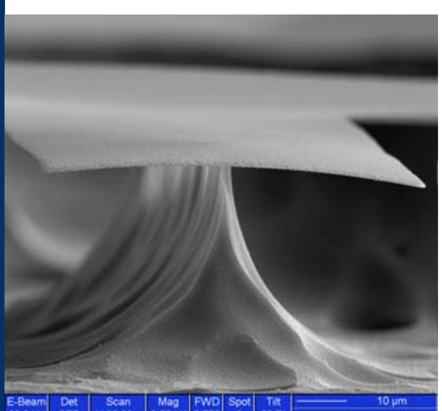
Cantilever Array Structures

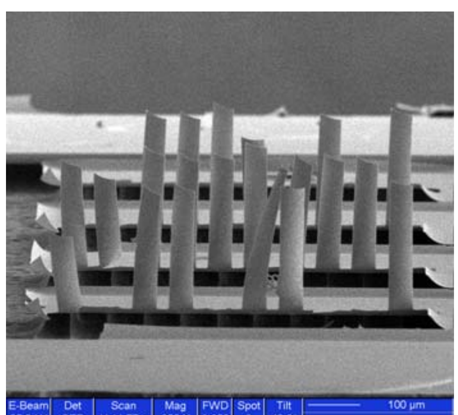
4. Definition of devices using photolithography

5. Etch heterostructure with Ar ion milling to expose Si substrate

6. Release cantilever structure from Si substrate with XeF_2 gaseous etchant

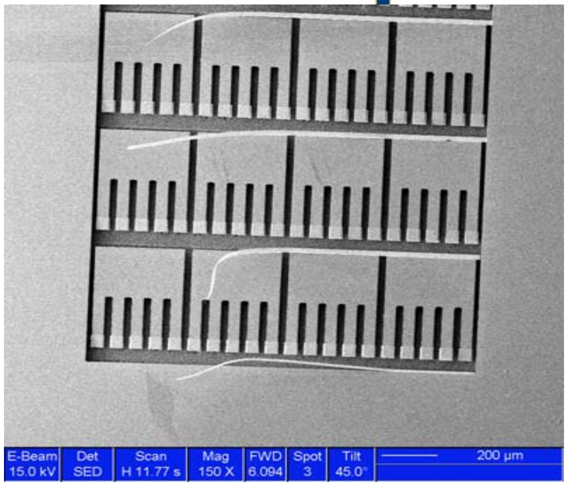


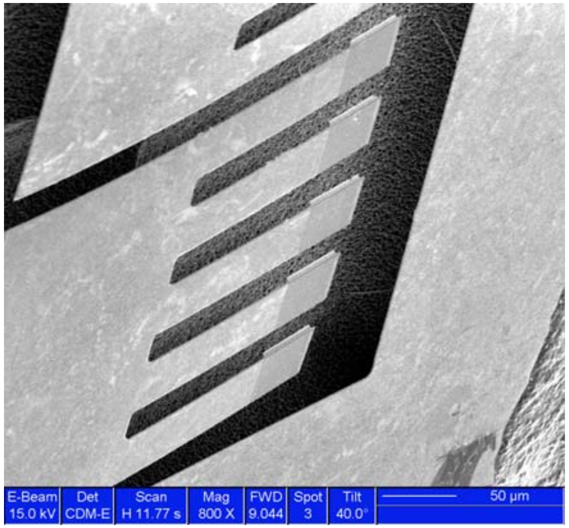




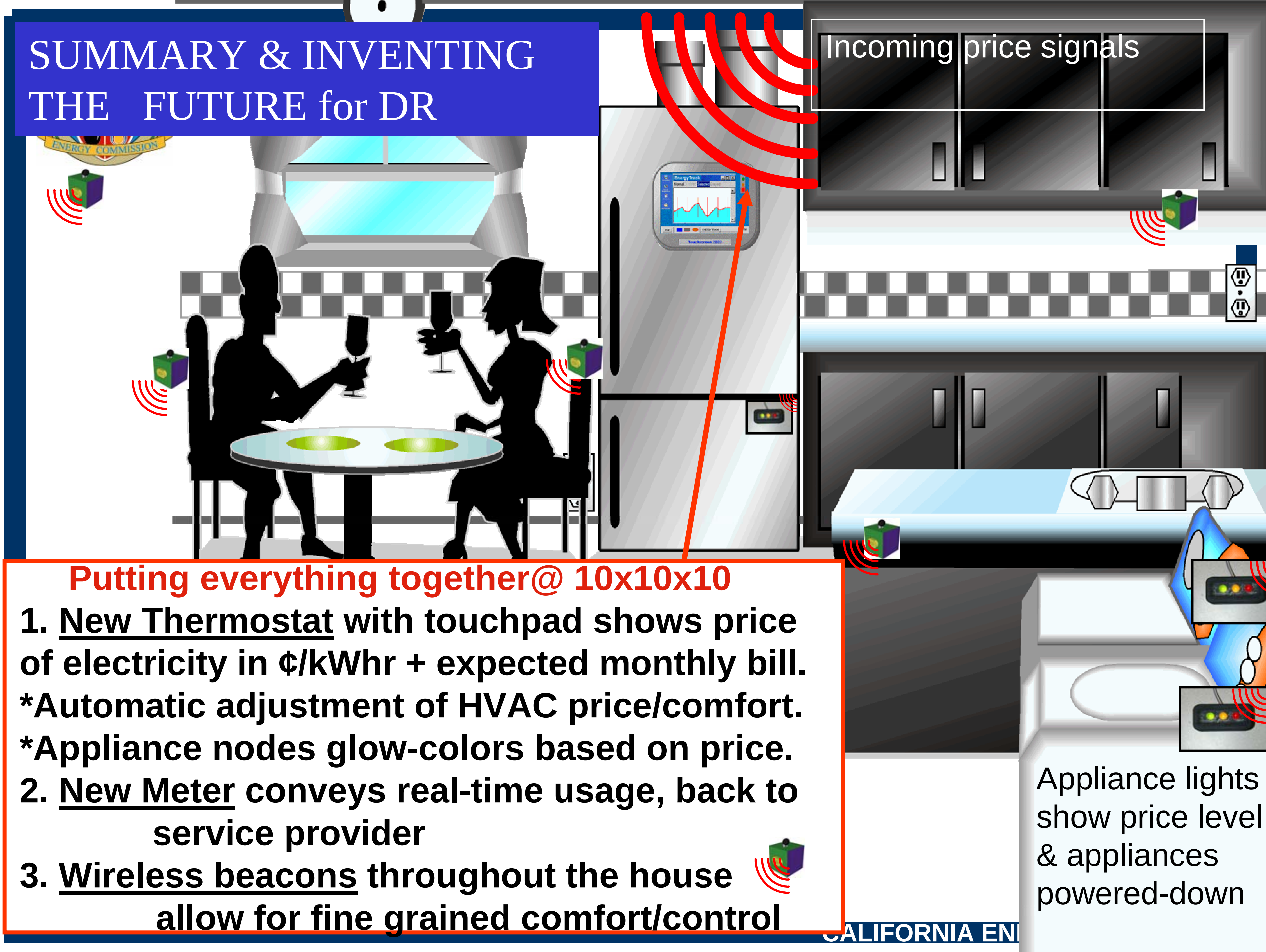
MEMS Findings for Power Supply

- Pulsed laser deposition can be used to grow epitaxial PZT films on Si substrate
- Thin film piezoelectric coefficient approaches bulk values, shows good switching capabilities
- Microscale cantilever resonant frequency 250-2500 Hertz, alternative design increase frequency
- Power modeling indicates a power density approaching 200 $\mu W/cm^3$
- Cantilever arrays fabricated and released using standard-CMOS compatible processes
- Residual stresses in film reduced





SUMMARY & INVENTING THE FUTURE for DR



Putting everything together@ 10x10x10

1. **New Thermostat** with touchpad shows price of electricity in ¢/kWhr + expected monthly bill.
*Automatic adjustment of HVAC price/comfort.
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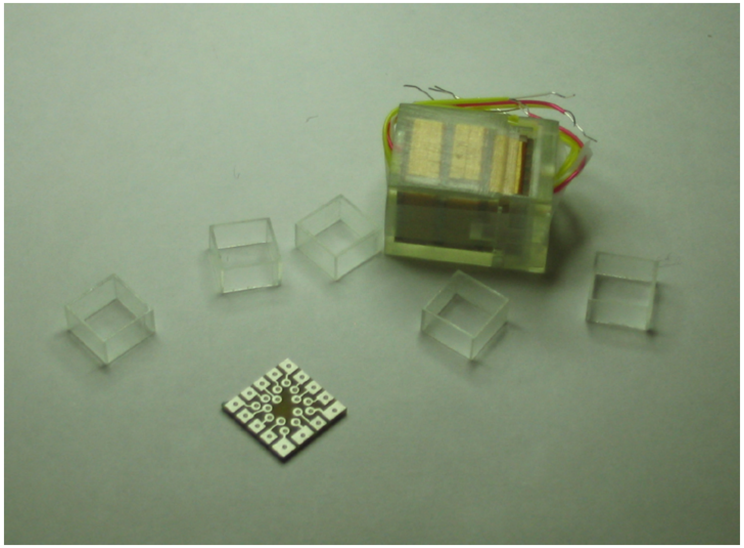
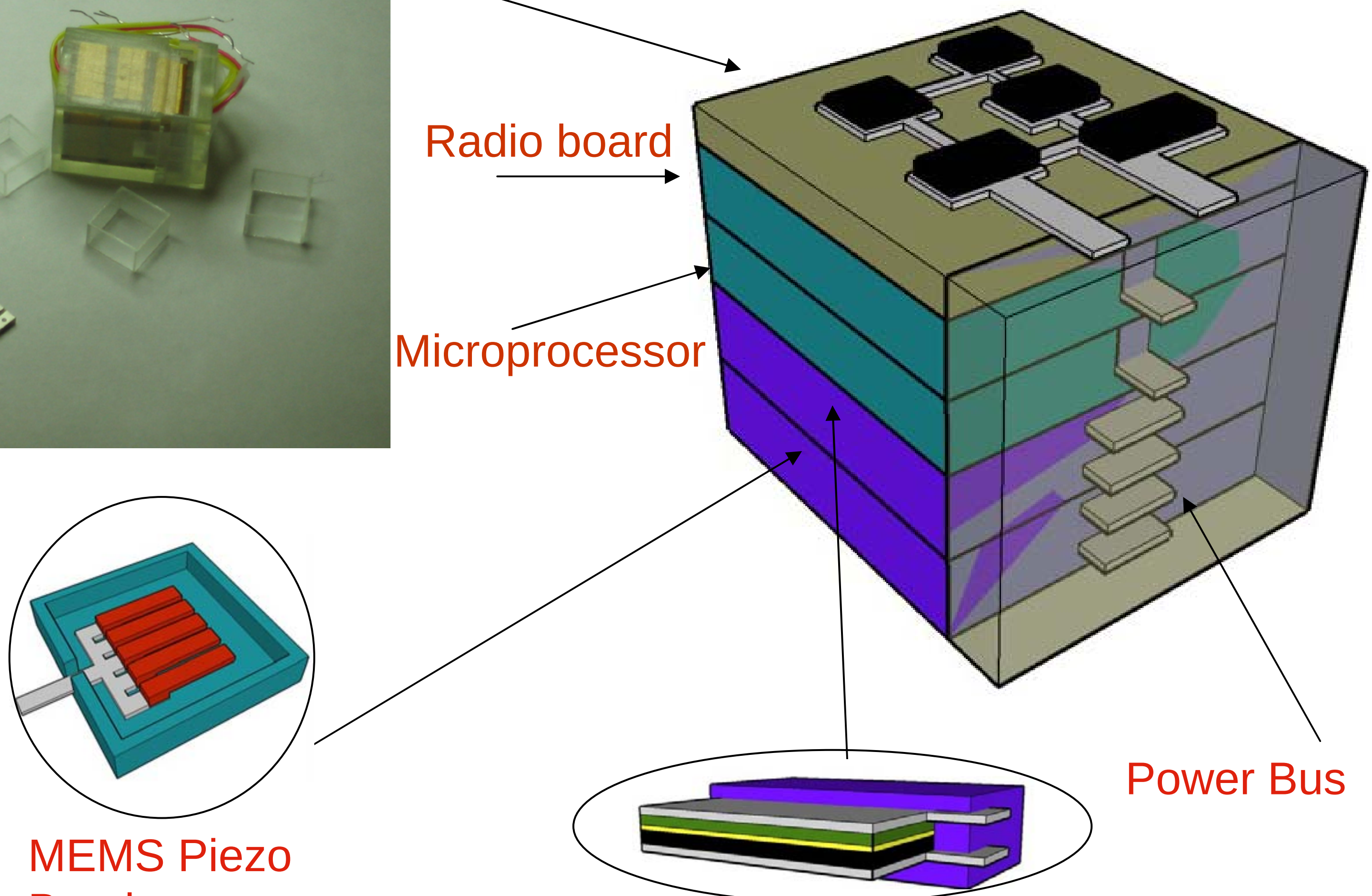
2. **New Meter** conveys real-time usage, back to service provider
3. **Wireless beacons** throughout the house allow for fine grained comfort/control

Beginning micro-integration and miniaturization to reduce DR's cost





DR Summary

- **Managing our summer peaks today is as big a job for society as was managing our per capita energy (kW-hr) needs in the last quarter of the 20th century**
- **However, this problem is different in that it involves complex information exchange and advanced communication systems**
- **Such communication needs the micro-integration of**
  - Low-power radios,
  - Mesh-networking,
  - MEMS-scale sensing,
  - MEMS scale power supplies, and
  - Micro-packaging-integration
  - All at “about a couple of dollars BOM per platform” range.
- **Such micro-integration will enable DR control and learning, for integration into meters, thermostats, temperature nodes**

Thanks to….

- **Of course, PIER/CEC**
- **Wireless Sensor Network suppliers**
  - Crossbow Inc. in San Jose CA
  - Dust Networks in Freemont CA
  - Moteiv in Berkeley CA
- **Wafers and chip prototyping**
  - Motorola
  - ST Microelectronics
- **Related industrial sponsors**
  - Honeywell
  - Alcoa

DR Summary

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